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(54) Distortion and noise reduction in wide band feedforward amplifier/mixer

(57) A front-end circuit for a radio receiver or spectrum analyser or similar device comprises an amplifier 88 with a feedforward loop around it. An error signal, representing the distortion introduced by the main amplifier, is subtracted from the amplified signal which includes the distortion. Controllable variable phase shift and controllable variable gain elements are introduced into the circuit so that the degree of distortion cancellation can be optimised, and kept at an optimum level to minimise the amount of distortion in the output signal at all operating conditions.

Other components of the receiver front end, such as the first mixer and the first IF filter, are included in the feedforward loop.

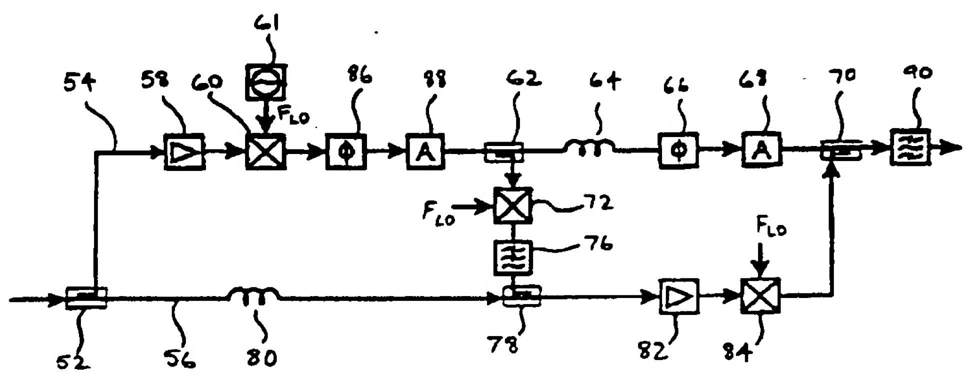

FIG. 3

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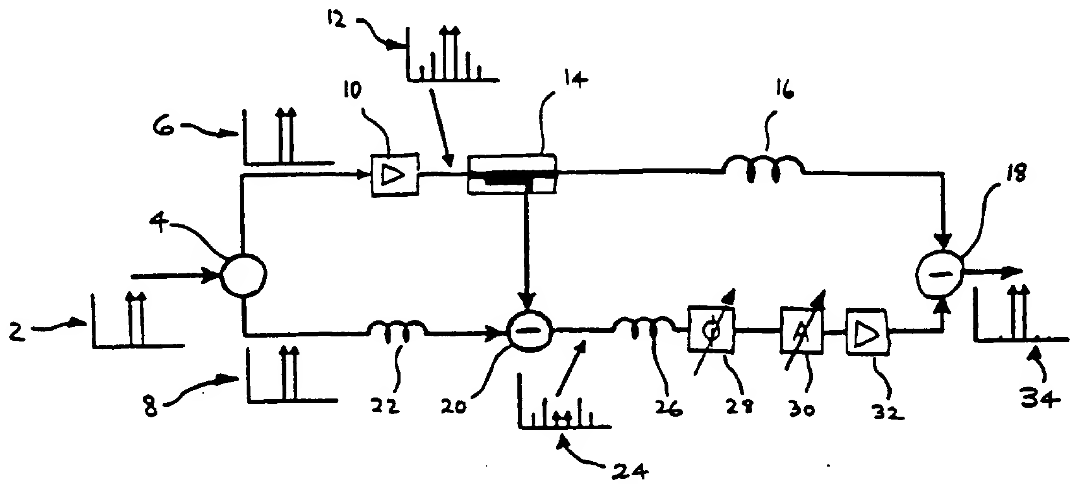
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FIG. 1

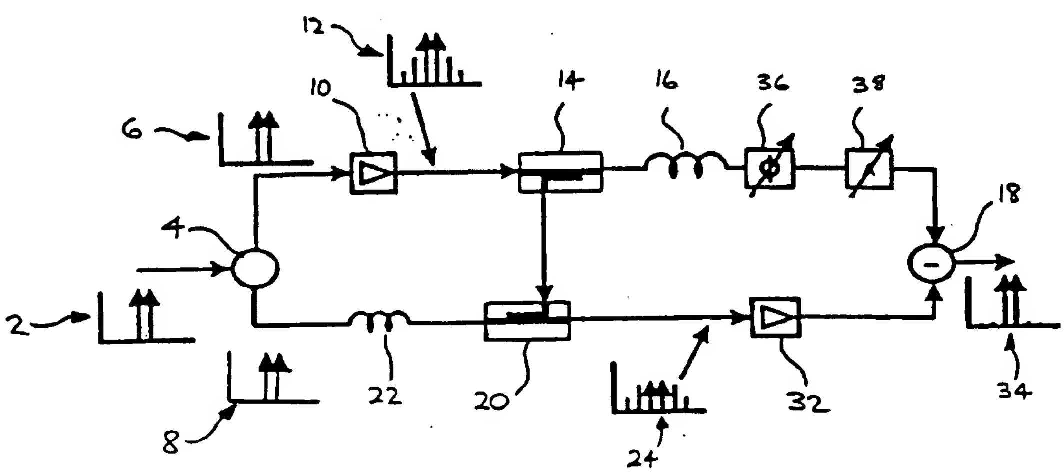
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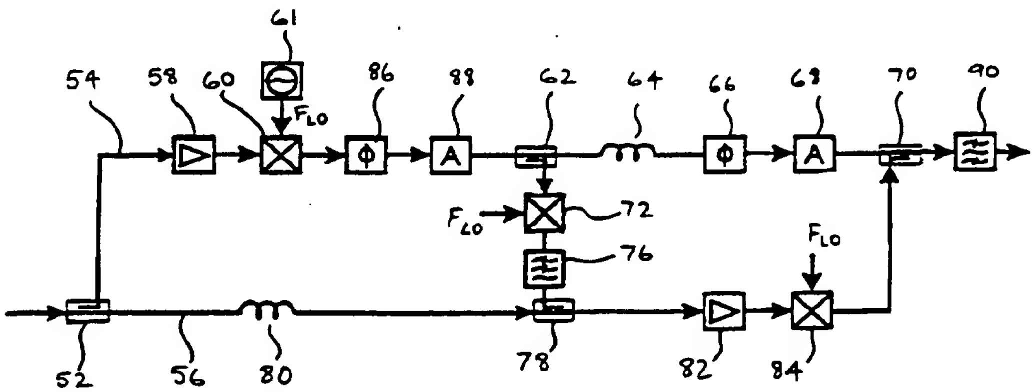
FIG. 2


61
54
58
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86
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F_{LO}
F_{LO}
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84

FIG. 3

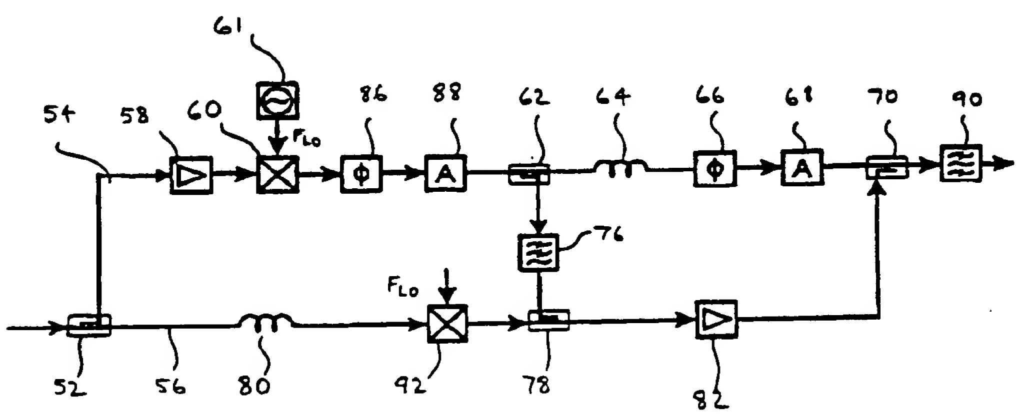
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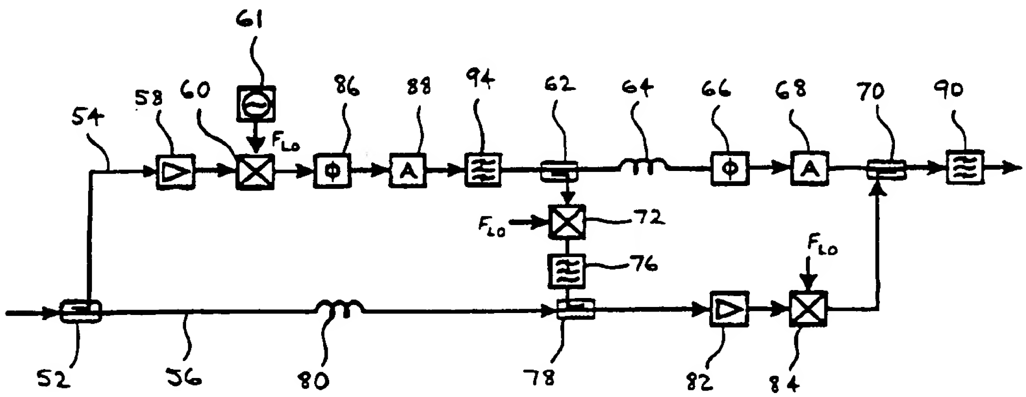
FIG. 4



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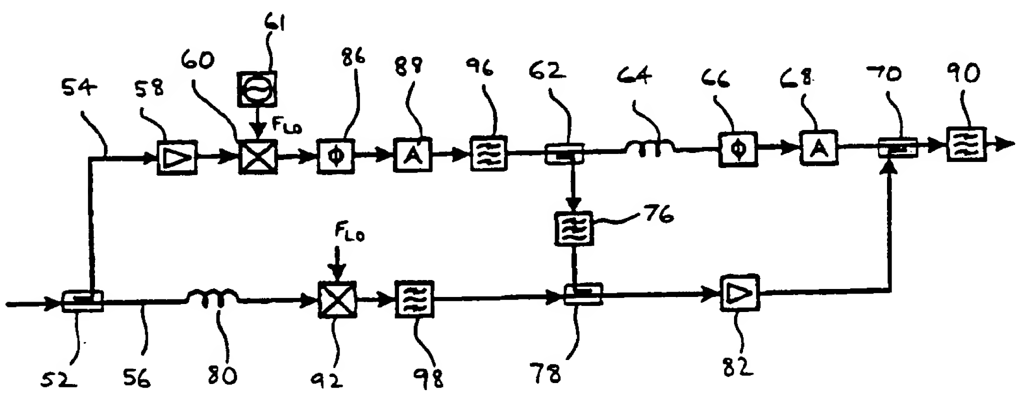
82
84

FIG. 5



61
54
58
60
F_{LO}
86
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96
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92
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FIG. 6

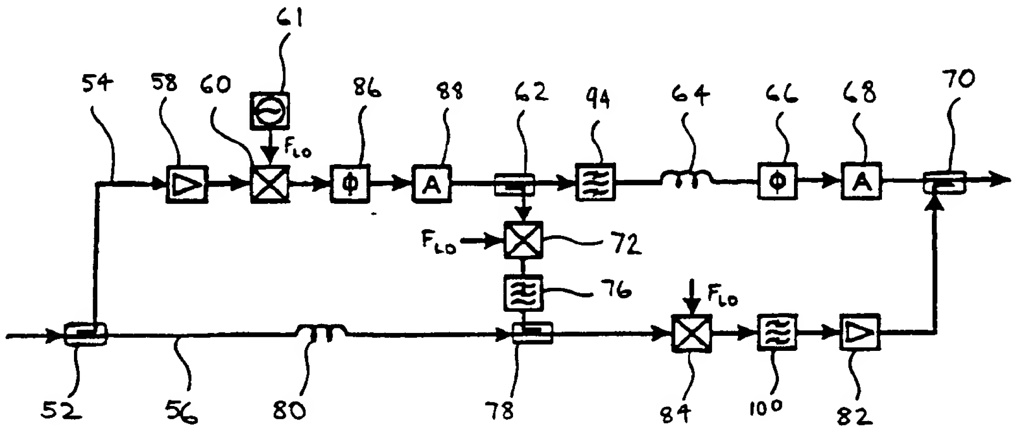
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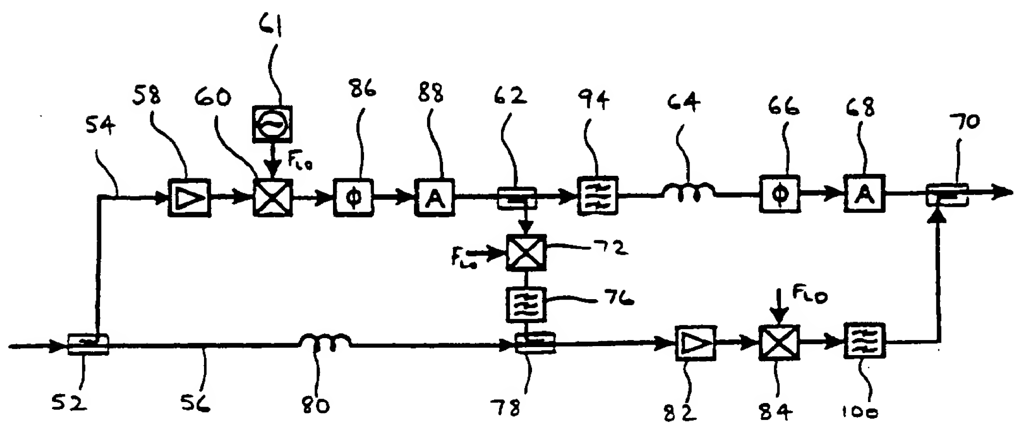
FIG. 7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F_LO
72
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84
100

FIG. 8

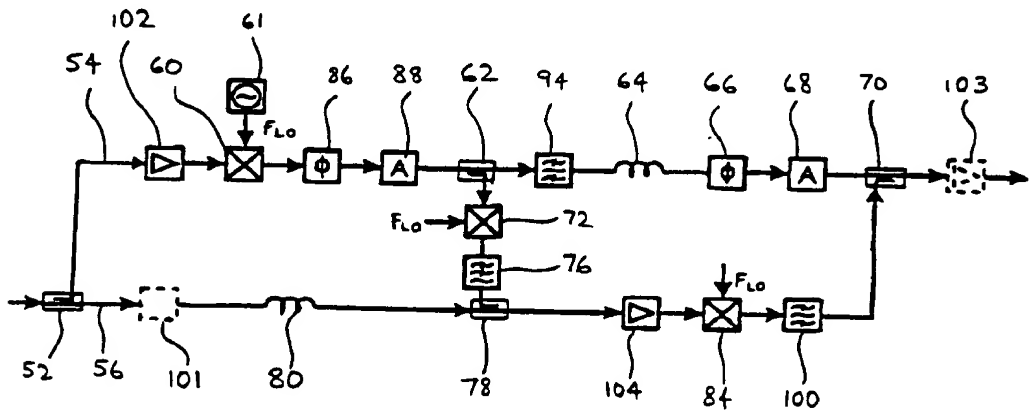
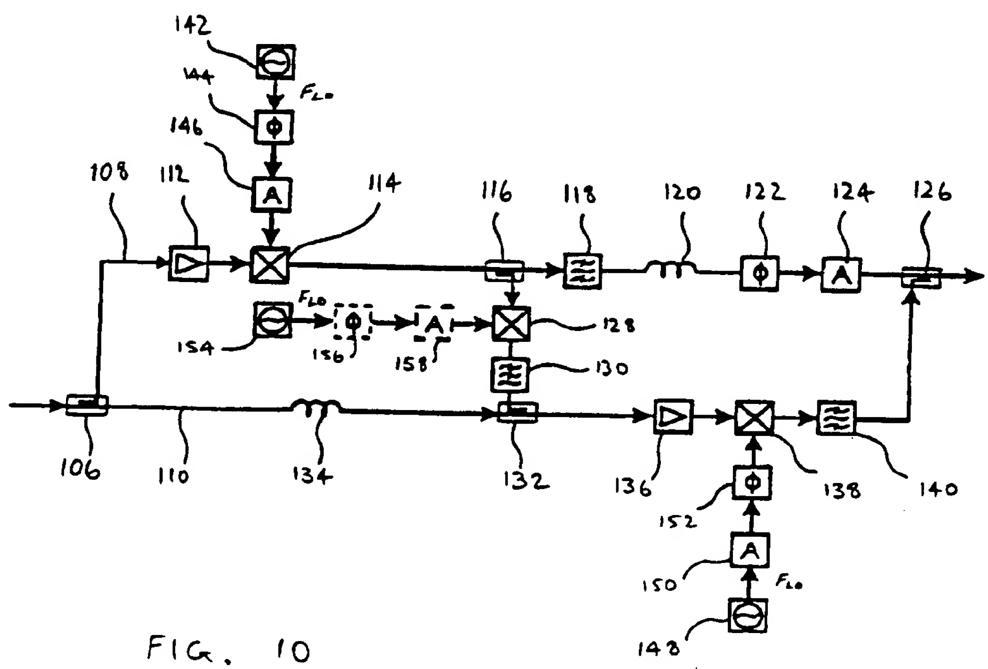

102
61
54
60
86
88
62
94
64
66
68
70
103
F_{LO}
F_{LO}
72
76
F_{LO}
52
56
101
80
78
104
84
100

FIG. 9


142
144
F_{LO}
146
108
112
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118
120
122
124
126
F_{LO}
154
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128
130
106
110
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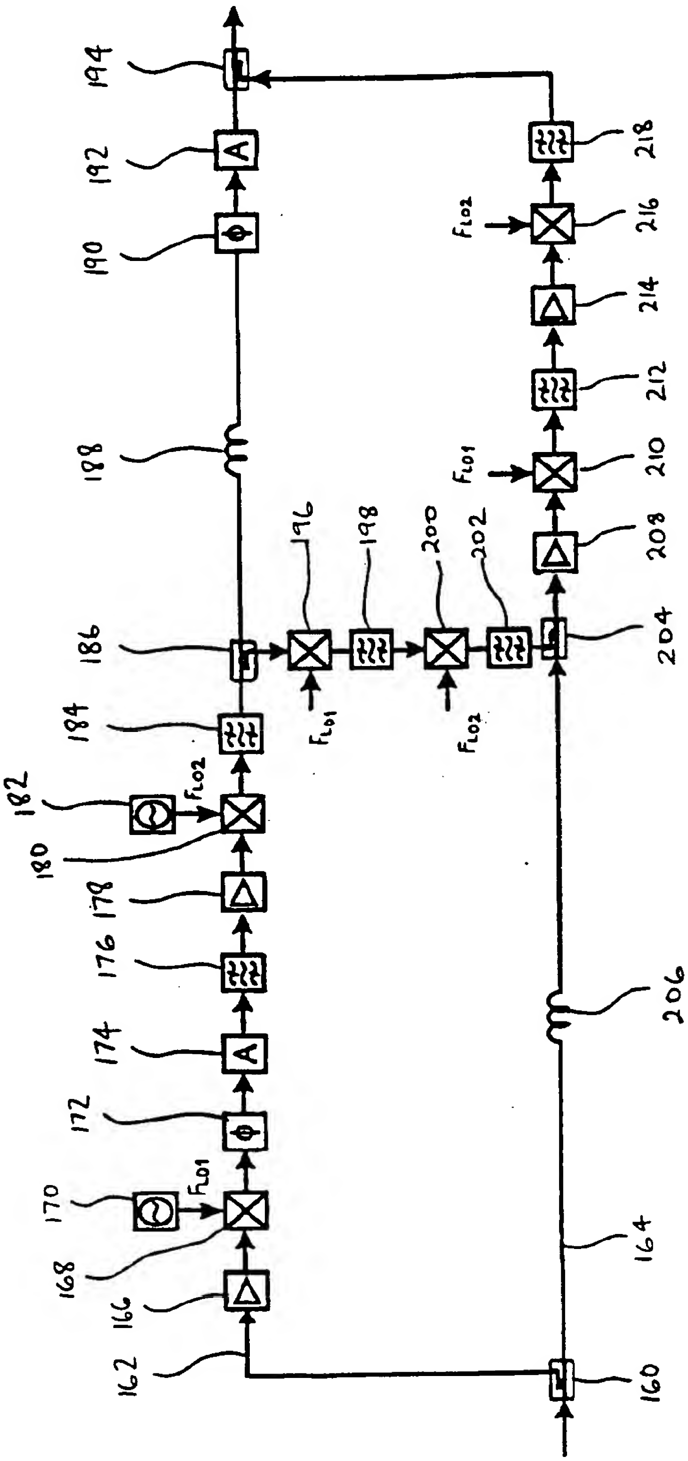
152
150
F_{LO}
148

FIG. 10


160
162
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F_{LO1}
172
174
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182
F_{LO2}
184
186
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192
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196
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202
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218
F_{LO1}
F_{LO2}
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A

FIG. 11

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RECEIVER CIRCUIT

The present invention relates to a receiver circuit, and in particular to a receiver front-end circuit which is linearized by the use of a feedforward arrangement.

In many situations it is important that front-end devices, such as pre-amplifiers and mixers, for example in radio receivers and spectrum analysers, have large dynamic ranges, without introducing noise into the signal. Accordingly, the present invention seeks to provide such front-end circuits in which the problems of noise, and of limited dynamic range, associated with prior art circuits, are at least alleviated.

GB-2244881 discloses a feedforward amplifier, for example for use in the transmitter circuits of a base station of a cellular telephone system. However, it has now been found, surprisingly, that an amplifier circuit of this general type can advantageously be used as a pre-amplifier in a radio receiver.

According to a first aspect of the present invention, there is provided a receiver circuit comprising a feedforward amplifier and mixer devices such that the feedforward loop involves frequency translation.

According to a second aspect of the present invention, there is provided a receiver circuit comprising, in combination, a front-end amplifier with feedforward control and a front-end mixer, the circuit configuration being such that it does not generate a preliminary amplified but untranslated output signal.

This contrasts with a conventional receiver circuit, in which a preliminary output from an amplifier circuit is supplied to a mixer.

According to a third aspect of the present invention, there is provided a receiver circuit, comprising:

a main amplifier;

means for generating an error signal from an input signal and a main amplifier output signal;

an error amplifier, for amplifying the error signal;

combining means for subtracting the error amplifier output signal from the main amplifier output signal;

means for frequency translating the signals such that the combining means operates at an intermediate frequency.

According to a fourth aspect of the present invention, there is provided a receiver circuit, including a feedforward amplifier, the amplifier comprising:

means for dividing an input signal into a first signal and a second signal;

a main amplifier, to which the first signal is supplied;

means for sampling the amplified first signal;

means for subtracting the sampled amplified first signal from the second signal to produce an error signal;

an error amplifier, to which the error signal is applied; and

means for subtracting the amplified error signal from the amplified first signal to produce an output signal; the amplifier further comprising:

means for controllably applying a variable phase shift and variable gain to either the error signal or the amplified first signal to minimise distortion in the output signal.

For a better understanding of the present invention, and to show how it may be put into effect, reference will now be made, by way of example, to the accompanying drawings in which:

Figure 1 is a schematic diagram of a front-end amplifier in accordance with one aspect of the invention;

Figure 2 is a schematic diagram of a second front-end amplifier in accordance with one aspect of the invention;

Figure 3 is a schematic diagram of a first receiver circuit including a front-end amplifier, and incorporating a mixer, in accordance with another aspect of the invention;

Figure 4 is a schematic diagram of a second receiver circuit in accordance with the other aspect of the invention;

Figure 5 is a schematic diagram of a third receiver circuit in accordance with the other aspect of the invention;

Figure 6 is a schematic diagram of a fourth receiver circuit in accordance with the other aspect of the invention;

Figure 7 is a schematic diagram of a fifth receiver circuit in accordance with the other aspect of the invention;

Figure 8 is a schematic diagram of a sixth receiver circuit in accordance with the other aspect of the invention;

Figure 9 is a schematic diagram of a seventh receiver circuit in accordance with the other aspect of the invention;

Figure 10 is a schematic diagram of an eighth receiver circuit in accordance with the other aspect of the invention; and

Figure 11 is a schematic diagram of a ninth receiver circuit in accordance with the other aspect of the invention.

As shown in Figure 1, an input signal 2 is divided by a splitter 4 into a main path signal 6 and a

reference path signal 8. The main path signal 6 is amplified by a conventional wideband, low-noise amplifier 10, and the amplified signal 12 is fed via a coupler 14 and time delay element 16 to an output coupler 18.

As can be seen, the amplified main path signal 12 includes distortion introduced by the amplifier 10. The coupler 14 takes a sample of the distorted main path signal 12, and feeds it to a subtracter 20. The reference path signal 8 is also fed to the subtracter 20 through a time delay 22. The subtracter 20 uses the undistorted reference path signal 8 to remove the component of the distorted amplified main path signal 12 which represents the input signal, and gives an output distortion signal 24 representing only the distortion added by the main path amplifier 10.

This distortion signal 24 is then fed through a time delay 26, a variable phase shifter 28, a variable gain element 30, and an error amplifier 32, and is then fed in anti-phase to the output coupler 18.

The effect of the output coupler is then that the distortion energy is subtracted from the amplified main path signal, so that the output signal 34 is, in the ideal case, an amplified but undistorted version of the original input signal.

The general principle of feedforward amplification is known, but the circuitry in accordance with the invention adds low-noise pre-amplification to a receiver circuit, without sacrificing the dynamic range of the circuitry to which the signal is applied.

One possible principle of operation of the automatic control of the phase shifter 28 and gain element 30 is described in more detail in GB-2244881, albeit not in the context of a receiver circuit. The contents of that document are incorporated herein by reference.

Other suitable control techniques are known, and any desired control technique may be used, such as using a pilot tone, either single-frequency, frequency hopped or direct-sequence spread-spectrum modulated.

Figure 2 shows an alternative form of a receiver circuit in accordance with the invention. It will be seen that the general form of the circuit is the same as the circuit shown in Figure 1, and elements of the circuit shown in Figure 2 having the same reference numerals as elements of the Figure 1 circuit have the same functions, and will not be described further.

The main difference between the two circuits is that the feedforward amplifier shown in Figure 2 includes a variable phase shifter 36 and variable gain element 38 in the main signal path (in place of the variable phase shifter 28 and variable gain element 30 in the error signal path in the embodiment of Figure 1). The arrangement of Figure 2 is advantageous because, in both of these circuits, any noise and distortion introduced by the error amplifier 32 are added directly into the output signal 34, and cannot be corrected (at least without the addition of a further feedforward loop). By contrast, noise in the main signal path, introduced by the main amplifier 10, is potentially removable. Clearly, an important aspect of circuits in accordance with the present invention, for use as low-noise front-end amplifier circuits, is to minimise the total noise and distortion. As a result, it is preferable to minimise the noise which is introduced by the error amplifier 32 (and which cannot be removed), even if this means a corresponding increase in the noise introduced by the main amplifier 10 (which potentially can be removed). Similarly, the overall noise figure is helped by using a coupler 20 as the subtracter, having minimum loss in the error signal path.

In the circuit of Figure 2, the variable gain element 38 (in practice, an attenuator) is in the main signal path and not the error signal path. The circuit of Figure 2 therefore has the advantage over the circuit of Figure 1 that it reduces the required gain of the error amplifier 32, and hence the levels of noise and distortion which it introduces. A further advantage is that, with the variable phase shifter 36 and variable gain element 38 in the main signal path, their loss, and the associated noise contribution, are removed from the error signal path.

It should be noted that the configuration shown in Figure 2 is practical for front-end amplifier circuits, although it may not be suitable for power amplifier circuits, because the signal levels present at the main amplifier output are still such that they can be handled by PIN diode attenuators and varactor diode phase shifters.

In all embodiments of the invention, any suitable components may be used as the variable gain and phase elements. For example a vector modulator and a variable gain amplifier may be used.

It can therefore be seen that feedforward amplifier circuits in accordance with the invention provide RF pre-amplification with lower noise and distortion than previous pre-amplifier circuits. In particular, the feedforward circuit can remove the distortion resulting from frequency and phase response anomalies of the main amplifier. The resulting amplifier circuit can have an extremely flat frequency response, particularly when compared with the frequency response of the main amplifier itself. Circuits in accordance with the invention may be used, for example, in measurement devices such as spectrum analysers, and in RF receiver front-ends.

When used in RF receiver devices, the amplifier

circuit shown in Figure 1 or 2 will supply its output signal 34 to a mixer device, for example an image-rejection mixer. It may be advantageous to combine the front-end amplifier and the first mixer, as this may improve the dynamic range of the mixer, albeit with some increased complexity.

In order to include the front-end mixer (and indeed subsequent elements such as the IF filter), it is necessary to modify the feedforward system by the inclusion of a number of mixing stages in addition to the mixing stage which is actually linearized, hence bringing about a new feedforward configuration, which involves frequency translation.

A combined feedforward front-end amplifier and first mixer is shown in Figure 3. An input signal is supplied to a directional coupler 52, which passes it into a main signal path 54 and an error signal path 56. The signal in the main signal path 54 is supplied to a low-noise amplifier 58. The output signal is then passed to a mixer 60, where it is mixed with a signal F_{LO} supplied by a local oscillator 61. The resulting signal then passes to a variable phase shifter 86, variable gain element 88, and directional coupler 62. As in the receiver pre-amplifier circuit described with reference to Figure 2, the signal then passes to a time delay element 64, variable phase shifter 66 and variable gain element 68, and then to an output coupler 70.

The sampled signal from the directional coupler 62 is supplied to a second mixer 72, to which is also supplied a local oscillator signal F_{LO}. The mixer 72 should preferably be a high-linearity device, at least at the relatively low-power signal levels which are present at that point in the circuit. The output from the mixer 72 is supplied to a low pass filter 76, which removes the unwanted mixer produces, and the output

signal at frequency $F_{IF} = F_{RF} - F_{LO}$ is supplied to a second directional coupler 78. A high pass filter to select the other mixer sideband could be used as an alternative. As further alternatives to achieve the same function, low or high pass filters could be placed after the other two mixers 60 and 84.

The error path signal in the error path 56 is supplied to a time delay 80, and then to the directional coupler 78, which acts as a subtracter. As before, the output of the coupler 78 now represents the distortion introduced by the amplifier 58. The resulting error signal is passed to an error amplifier 82, and then to a third mixer 84, to which is also supplied a local oscillator signal F_{LO}. The resulting signal is then passed to the output coupler 70, where it is subtracted from the main path signal, to give a low distortion intermediate frequency output, which can be passed to an IF filter 90.

It will be noted that the lower signal path 56, from the input through to the error amplifier 82, uses only directional couplers 52, 78. This has the advantage that, because such couplers have extremely low losses, the noise figure of the system, which is almost entirely determined by the loss in this part of the system, can be reduced.

The noise figure is also improved by the placement of the gain and phase controllers in the upper signal path 54. These devices are advantageously placed after the main amplifier 58, as signals at this point are still at a sufficiently low level to allow the gain and phase control elements to be relatively small and of reasonable cost. This contrasts with a power amplifier system, in which the signal levels following the main amplifier would be rather high. It should be noted, however, that the gain and phase control elements may be placed at any suitable location within the system,

for example before or after the main amplifier and/or mixer; before or after the first time delay element; before or after the second mixer and/or filter; before or after the second time delay element; or before or after the error amplifier and/or mixer.

It will be noted that incorporating the front-end mixer of the receiver circuit into the feedforward system requires the provision of frequency translation at more than one location, with the exact positions of the frequency translating elements (mixers in Figure 3) requiring careful consideration. The placement of the first mixer 60 after the main amplifier 58 ensures that the noise figure of that amplifier is not degraded by the poor noise figure of the mixer. (Even though the intention of the feedforward loop is effectively to improve the noise figure of the amplifier, it is preferable not to degrade that noise figure unnecessarily).

It should be noted that, although the third mixer 84 could in theory be included in the error signal path before the error amplifier 82, such an arrangement would be disadvantageous, as this would cause a significant deterioration in the noise figure available. When positioned as shown after the error amplifier 82, the third mixer 84 will still be receiving a rather low-power signal, and so will not suffer difficulties caused by its dynamic range, unless the gain of the system is excessive, or the input signals are of particularly high power.

Figure 4 shows an alternative system having a similar function to the system shown in Figure 3. Components of the system shown in Figure 4 having the same function as elements of the system shown in Figure 3 are indicated by the same reference numerals, and will not be described further. The configuration shown in Figure 4 replaces the second and third mixers 72, 84

in the Figure 3 configuration with a single mixer 92. It will be noted that this configuration is simpler, and will be acceptable for many applications. However, this arrangement is less advantageous than the configuration shown in Figure 3, as the system noise figure is degraded by the placement of the mixer 92 in the lower signal path 56, and the loss in this mixer will thus contribute directly to the noise figure. In addition, any distortion introduced by the mixer 92 under extreme signal conditions will not be able to be removed by the feedforward linearization process.

The mixer 92 may be placed before or after the time delay element 80, and of course the alternative locations for the gain and phase control elements, mentioned in connection with Figure 3 are still possible in the embodiment shown in Figure 4.

In particularly preferred embodiments of the present invention, the first IF filter is incorporated in the feedforward amplifier circuitry. A configuration embodying this concept is shown in Figure 5, in which reference numerals indicating components having the same functions as elements of the Figure 3 circuit are indicated by the same reference numerals, and will not be described further.

The circuit of Figure 5 differs from the circuit shown in Figure 3, in that the first IF filter 94 of the receiver circuit is incorporated in the amplifier feedforward circuitry. In Figure 5, the filter 94 is shown placed after the phase control element 86 and gain control element 88, although it could be placed anywhere in the top signal path 54 following the first mixer 60.

An advantage of incorporating the filter 94 in this circuit is that the subtraction process which takes place in the lower path coupler 78 is now essentially a narrow-band operation. As a result, the

error signal can be of a very high quality, in the sense that the degree of residual input signal energy in the error signal will be very small. This will be of advantage in many of the control processes which may be used to control the system to maintain the distortion cancellation.

A further advantage is that the distortion cancellation, in the output coupler 70, is also a narrow-band process. The bandwidth is determined by the bandwidth of the IF filter 94, and, in the case of an FM system, for example, the bandwidth may typically be around 25 kHz. It should be possible to achieve an extremely high degree of cancellation in this narrow bandwidth, thus giving excellent overall system performance.

System performance using any of the embodiments of the invention described herein should be greatly superior to circuits using conventional feedforward technology.

It can thus be seen that such a system can produce excellent performance, because the circuit should not only provide good distortion removal, but should also provide signals which allow very high quality control of the cancellation process. It is of course this control which is essential to maintain a high degree of cancellation.

Figure 6 shows an alternative configuration of a front-end incorporating the IF filter, in this case being based on the circuit shown in Figure 4. Again, elements having the same function as elements of the circuit shown in Figure 4 are indicated by the same reference numerals, and will not be described further. As in the embodiment shown in Figure 4, this circuit requires only two mixers 60, 92. However, in this embodiment, it is necessary to use two IF filters 96, 98, in the upper and lower signal paths 54, 56

respectively.

As discussed with reference to Figure 4, this arrangement has some disadvantages as regards the system noise figure, but in fact this configuration suffers less from this disadvantage than the Figure 4 circuit. This is because, whereas in the Figure 5 circuit a long (and hence potentially lossy and/or noisy) lower-path time delay element 80 is needed in order to compensate for the delay through the IF filter 94, in the Figure 6 configuration the time delay needs to be less long, because the delay through the IF filter 96 is equalized by the delay in the lower path IF filter 98.

A third IF filter 90 is shown at the output of the system, but in fact this is only required where the IF filters 96, 98 are broader band, as they may be chosen to be in order to reduce their time delay. The incorporation of an output IF filter 90 may be required particularly in the Figure 5 embodiment, where, if the upper path IF filter 94 is given a narrow bandwidth, a very long delay may need to be introduced in the lower path by means of the time delay element 80. If the filter 94 has a broader bandwidth, the size of the time delay can be reduced, with the final channel filtering then performed at the output of the loop.

Figure 7 shows a further embodiment of a receiver circuit having the same functionality. Again, elements having the same functions as elements of the circuit shown in Figure 5 are indicated by the same reference numerals, and will not be described further. In the circuit shown in Figure 7, the error signal downconversion mixer 84 is placed before the error amplifier 82, and the downconverted error signal is filtered in a further IF filter 100 before amplification. This has the disadvantage that the system noise figure is degraded, for the reasons

discussed above with reference to Figures 4 and 6, but has the significant advantage that the required dynamic range of the error amplifier 82 is thereby significantly reduced. The error amplifier 82 is now required only to amplify the distortion present on a single channel, rather than attempting to reconstruct the complete broad band input spectrum, which may contain a number of very strong unwanted signals.

The circuit shown in Figure 7 also has the first IF filter 94 placed after the sampling coupler 62. This avoids the problem discussed previously that the time delay element 80 will need to be large in order to compensate for the filter 94, and hence will be lossy and/or noisy. However, placing the filter 94 in this position reintroduces the problem that the coupler 62 now needs to effect a broad band subtraction. However, this can be controlled by using the processed error signal at the output of the lower path IF filter 100 or the error amplifier 82, which will be narrow band, to allow high quality control on the required channel.

An advantage of placing the IF filter 94 following the coupler 62 is that the filters 94, 100 will have very similar time delays, thus significantly reducing the size and loss of the time delay element 64. In many configurations in which narrow band cancellation is required, such as the configurations shown here involving IF filters, the sizes and delays of the time delay elements can be reduced very significantly, or even eliminated. In many single channel receiver systems, the bandwidth restriction which this imposes will not be a problem.

Figure 8 shows a further alternative configuration. As before, elements having the same function as elements of the circuit shown in Figure 7 have the same reference numerals and will not be described further.

The circuit shown in Figure 8 differs from the circuit shown in Figure 7 only in that the mixer 84 and IF filter 100 are now placed after the error amplifier 82. This has the advantage that the system noise figure is optimised, although it requires a larger dynamic range from the error amplifier. However, this disadvantage should be relatively small because the error amplifier will be dealing with error signals, which have had the input signal energy largely removed, and which should have a significantly smaller dynamic range than the dynamic range of the input signals. Hence, the required increase in dynamic range of the error amplifier 82 should be small.

It will thus be seen that there are a large number of alternative configurations having the same general function. In addition to the different configurations shown in Figures 5-8, there are other modifications which can be made. For example, the high pass filter 76 may be removed or replaced by a low pass or band pass filter. The variable gain and phase elements could be redistributed between the various paths, for example as described above with reference to Figure 3, and could be split between the paths, for example with the phase shift element in the lower path and the variable gain element in the upper path. The mixing elements could also be redistributed between the various paths. Other filters, attenuators and time delay elements could be incorporated at various points, again without altering the basic function of the circuit. The various couplers could be replaced by hybrid (e.g. transformer-based) splitters, subtractors and combiners, or even summing and/or splitting semiconductor devices such as operational amplifiers. Finally, it will be recognised that the complete system could be implemented in various ways directly as an integrated circuit.

Figure 9 shows a further alternative circuit configuration having the same function as the circuit shown in Figures 5-8. As before, circuit elements having the same functions as elements of the Figure 8 circuit have the same reference numerals, and will not be described further.

In the circuit shown in Figure 9, the main amplifier 102 has a logarithmic response characteristic. This will compress the system dynamic range, and may help to reduce the level of distortion which needs to be suppressed. The error amplifier 104 may be an antilog amplifier, since it will act to restore the system response to that of the input signals, effectively undoing the effects of the log characteristic of the main amplifier 102. Alternatively, an element 101 with a log characteristic may be inserted in the lower path 56, in which case an antilog amplifier 103 will need to be provided at the system output.

The circuits described so far have all included only a single feedforward cancellation process. It will be appreciated that feedforward correction may be applied many times in order to obtain the required degree of distortion removal. In such a case, the complete feedforward system forms the "main amplifier" element in a new feedforward system. Alternatively, the error amplifier may be repeatedly linearized by a number of feedforward processes.

Figure 10 shows an alternative circuit configuration, again having the same general function as the circuits shown in Figures 5-9. In the circuit shown in Figure 10, an input signal is supplied to a directional coupler 106, which passes it into a main signal path 108 and an error signal path 110. The signal in the main signal path 108 is supplied to a low noise amplifier 112. The amplified signal is then

passed to a mixer 114, and the resulting signal passes to a directional coupler 116. The signal then passes to a first IF filter 118, time delay element 120, variable phase shifter 122 and variable gain element 124, and then to an output coupler 126.

The sampled signal from the directional coupler 116 is supplied to a second mixer 128, and then to a high pass filter 130, and the output signal is supplied to a directional coupler 132. The signal in the error path 110 is supplied to a time delay 134, and then to the directional coupler 132, which acts as a subtracter. As previously, the output of the subtracter 132 now represents the distortion introduced by the amplifier 112. The error signal is passed to an error amplifier 136, and then to a third mixer 138 and a second IF filter 140. The resulting signal is then passed to the output coupler 126, which subtracts it from the main path signal, to give an output signal.

This configuration differs from the configurations described previously most noticeably in that the local oscillator signal F_{LO} is supplied to the mixer 114 from a local oscillator 142 through controllable phase change element 144 and controllable gain element 146, while the local oscillator signal F_{LO} to the mixer 138 is supplied from a local oscillator 148 through gain control element 150 and phase control element 152. In such a configuration, the local oscillator signal F_{LO} may be supplied to the mixer 128 direct from a local oscillator 154, but the phase control element 144 and gain control element 146 may be replaced by a phase control element 156 and gain control element 158 shown in dashed lines in Figure 10. The automatic control techniques used to control the gain and phase elements may be the same as those used in the earlier embodiments. As before, one possible control technique is disclosed in GB-2244881, but it will be appreciated

that any suitable control technique may be used.

The various local oscillators will need to be on the same frequency, and would preferably be phase-locked together, or may alternatively be split from a common single local oscillator using, for example, a power splitter.

An advantage of applying the gain and phase control to the local oscillator signals is that control only needs to be provided at a single frequency at any time, and so the gain and phase controllers do not need good wide band frequency characteristics. In addition, as they only operate at a single frequency tone, and are outside the signal paths of the system, their distortion performance is unimportant. Finally, again as they are not in the signal path, their through-path signal loss is unimportant.

Embodiments of the invention described with reference to Figures 1-10 show the incorporation of the front-end, first mixer and first IF filter in the feedforward loop. Further advantages may be gained by including further elements of the receiver chain, up to and including parts of the base band digital signal processor (DSP). A circuit illustrating this principle is shown in Figure 11. In the circuit of Figure 11, an input signal is supplied to a directional coupler 160, which passes it into a main signal path 162 and an error signal path 164. The signal in the main signal path 162 is supplied to a low noise amplifier 166, the output signal of which is passed to a mixer 168, where it is mixed with a signal F_{LO1} supplied by a first local oscillator 170. The resulting signal then passes to a variable phase shifter 172, variable gain element 174, and a first IF filter 176. The filtered signal passes to a second amplifier 178, and second mixer 180, where it is mixed with a signal F_{LO2} supplied by a second local oscillator 182. The resulting signal is supplied

to a second IF filter 184, and then to a directional coupler 186, following which the signal passes to a time delay element 188, variable phase shifter 190, variable gain element 192, and an output coupler 194.

The sampled signal from the directional coupler 186 is supplied to a third mixer 196, which also receives the first local oscillator signal F_{LO1}, a second IF filter 198 operating at the first local oscillator frequency, a fourth mixer 200, which also receives the second local oscillator signal F_{LO2}, and a second IF filter operating at the second IF frequency 202. The output signal is supplied to a further directional coupler 204.

The error path signal in the error path 164 is supplied to a time delay 206, and then to the directional coupler 204, which acts as a subtracter. The output of the coupler 204 now represents the distortion which is to be cancelled. The error signal is passed to a first error amplifier 208, a fifth mixer 210, which also receives the first local oscillator signal F_{LO1}, a third IF filter 212 operating at the first IF frequency, a second error amplifier 214, a sixth mixer 216 which also receives the second local oscillator signal F_{LO2}, and a third IF filter 218 operating at the second IF frequency. The resulting signal is then passed to the output coupler 194, to give an output signal which can be processed further.

Circuits of this type potentially allow the whole of the receiver circuitry to be linearized, allowing both strong and weak signals to be received simultaneously.

This may be particularly useful, for example, in the receiver circuits of a base station of a cellular mobile radio system, particularly one which uses an adaptive antenna array. Receiver circuits according to the invention are also of particular use in mobile and

handportable transceivers, spectrum analysers and test-instrument applications, and in general broadband receivers, particularly in situations where a large dynamic range is required, i.e. the ability to receive small wanted signals in the vicinity of large unwanted signals.

A particular advantage of the invention is that, in several of the disclosed circuit configurations, one or both of the cancellation processes is narrow band. It is therefore not necessary for the loop to be capable of broad band coverage, and so one or both of the time delay elements can be removed. This is of particular advantage in integrated circuit implementations of the invention, as the fabrication of large time delay elements is difficult in integrated circuits.

Without the time delays, the circuit will only provide good cancellation over a narrow frequency band, but this may not be an important disadvantage, because the point at which cancellation occurs will be determined by the local oscillator frequency (In the case of the distortion removal cancellation process, cancellation will occur at the IF frequency.) The circuit can therefore operate over a very wide frequency range, with good cancellation and, often, no requirement for time delay elements.

There are thus disclosed receiver circuits which have significant advantages over the conventional devices.

CLAIMS

1. A receiver circuit comprising a feedforward amplifier and mixer devices such that the feedforward loop involves frequency translation.

2. A receiver circuit as claimed in claim 1, further comprising at least one intermediate frequency filter in the feedforward loop.

3. A receiver circuit as claimed in claim 2, further comprising additional mixer devices, such that the feedforward loop involves first and second stages of frequency translation.

4. A receiver circuit as claimed in claim 3, comprising, in the feedforward loop, filters operating at first and second intermediate frequencies.

5. A receiver circuit comprising, in combination, a front-end amplifier with feedforward control and a front-end mixer, the circuit configuration being such that it does not generate a preliminary amplified but untranslated output signal.

6. A receiver circuit, comprising:

a main amplifier;

means for generating an error signal from an input signal and a main amplifier output signal;

an error amplifier, for amplifying the error signal;

combining means for subtracting the error amplifier output signal from the main amplifier output signal;

means for frequency translating the signals such that the combining means operates at an intermediate frequency.

7. A receiver circuit, comprising:

a main amplifier for receiving an input signal, and generating a main amplifier output signal;

means for deriving an error signal from the input signal and the main amplifier output signal, the error

signal being representative of the distortion introduced by the main amplifier;

means for subtracting the error signal from the main amplifier output signal to produce an output signal with distortion cancellation;

means for applying automatic gain and phase control to the error signal and/or the main amplifier output signal to maximise the degree of distortion cancellation; and

frequency translation means for downconverting the main amplifier output signal and the error signal to an intermediate frequency before applying the distortion cancellation.

8. A receiver circuit, comprising:

a main amplifier;

means for generating an error signal from an input signal and a main amplifier output signal;

means for frequency translating the main amplifier output signal and the error signal to an intermediate frequency;

an intermediate frequency filter for filtering the frequency translated main amplifier output signal;

an error amplifier, for amplifying the error signal before or after frequency translation;

combining means operating at the intermediate frequency for subtracting the frequency translated error amplifier output signal from the frequency translated main amplifier output signal.

9. A receiver circuit as claimed in claim 8, further comprising means for applying automatic gain and phase control to signals at selected points in the circuit to maximise the degree of distortion cancellation obtained by said combining means.

10. A receiver circuit as claimed in claim 9, comprising means for applying automatic gain and phase control to the frequency translated main amplifier

output signal.

11. A receiver circuit as claimed in claim 9, wherein the means for frequency translating the main amplifier output signal and the error signal comprises a local oscillator, and comprising means for applying automatic gain and phase control to a local oscillator signal.

12. A receiver circuit, comprising:

a main amplifier for receiving an input signal, and generating a main amplifier output signal;

means for deriving an error signal from the input signal and the main amplifier output signal, the error signal being representative of the distortion introduced by the main amplifier;

means for subtracting the error signal from the main amplifier output signal to produce an output signal with distortion cancellation;

means for applying automatic gain and phase control to the error signal and/or the main amplifier output signal and/or the input signal to maximise the degree of distortion cancellation;

frequency translation means for downconverting the main amplifier output signal and the error signal to an intermediate frequency before applying the distortion cancellation; and

an intermediate frequency filter for filtering the main amplifier output signal before applying the distortion cancellation.

13. A receiver circuit, comprising:

a main amplifier, for generating an amplified signal from an input signal;

means for applying a local oscillator signal to downconvert the amplified signal to an intermediate frequency;

means for generating an error signal at the intermediate frequency indicative of the distortion

introduced by the main amplifier;

means for subtracting the error signal from the downconverted amplified signal to generate an intermediate frequency output signal with distortion cancellation; and

means for applying gain and phase control to at least one signal in the receiver circuit to maximise the distortion cancellation.

14. A receiver circuit as claimed in claim 13, further comprising an intermediate frequency filter, to which is applied the downconverted amplified signal.

15. A receiver circuit, including a feedforward amplifier, the amplifier comprising:

means for dividing an input signal into a first signal and a second signal;

a main amplifier, to which the first signal is supplied;

means for sampling the amplified first signal;

means for subtracting the sampled amplified first signal from the second signal to produce an error signal;

an error amplifier, to which the error signal is applied; and

means for subtracting the amplified error signal from the amplified first signal to produce an output signal; the amplifier further comprising:

means for controllably applying a variable phase shift and variable gain to either the error signal or the amplified first signal to minimise distortion in the output signal.

16. A receiver circuit as claimed in claim 15, wherein the variable phase shift and variable gain are applied to the amplified first signal.

17. A receiver circuit as claimed in any one of claims 6 to 16, wherein the main amplifier has a logarithmic response characteristic.

18. A mobile radio system base station, a mobile/handportable radio transceiver, a spectrum analyser or test instrument, or a broadband radio receiver, including a receiver circuit as claimed in any preceding claim.